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Summary

Satellite broadcasting tests of television with two sound channels digitally modulated onto a subcarrier were carried out through the European Orbital Test Satellite (OTS). The parameters of the sound system (subcarrier amplitude and frequency) were varied during the experiments and error rates were measured in the sound channels. The tests confirmed the feasibility of the method for satellite broadcasting in the future.

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1. Introduction

As a result of the planning of satellite broadcasting in the 11.7 – 12.5 GHz band, culminating in the World Administrative Radio Conference on satellite broadcasting (WARC – SB) in Geneva in 1977, it was agreed that for ITU Regions 1 and 3 each broadcast channel would be 27 MHz wide. Planning was based on a frequency modulated television signal using the standards current in the country concerned, together with one frequency-modulated sound subcarrier. But no particular constraints were placed on the number of associated sound channels or the method used to accommodate them providing any interference caused was no greater than that caused by the reference system. Many countries may wish to take advantage of this freedom of choice to gain extra channels for multilingual commentaries or for stereophonic sound.

The EBU is currently studying several different television sound systems carrying between two and eight separate high-quality channels. Amongst the various techniques that are currently being considered for accommodating two or more sound channels, the use of a digitally modulated subcarrier appears to offer positive advantages. Two important advantages may be mentioned.

(1) The presence of noise, interference and non-linearity in the transmission path all effect the error rate only. When a suitably low error rate is achieved the sound quality is unimpaired and there is no cross-coupling between the channels.
(2) Advances in integrated circuit techniques should lead to the development of domestic receivers with cheap and very reliable sound sections.

This report describes broadcasting tests carried out through the Orbital Test Satellite (OTS) using one possible method of carrying digital two channel or stereophonic sound on a subcarrier using 4-phase d.p.s.k. The up-link to the satellite (in the 14 GHz band) was established from the earth terminal at Goonhilly with the co-operation of the Post Office. The satellite down-link signals (in the 12 GHz band) were received by the BBC small earth terminal at Kingswood Warren.

2. The base-band sound system

The digital coding and serialization of the two audio channels are fully described elsewhere.[1] In short, the signals are sampled at 32 kHz and digitally compressed from 13 bits to 10 bits per sample with the addition of occasional 2 bit words to describe the scale factor of the compressor. The complete bit-stream, with parity and framing bits, emerges at 704 kbit/s.

The decoder detects the framing pattern and looks for parity errors in each sample word. If an error is detected, the previous word is repeated. The equipment was designed for high quality sound distribution, and includes a unit which mutes the sound output in the event of high error rates. This unit was disabled for the broadcast tests to permit investigation through the threshold condition.

3. The 4-phase d.p.s.k. equipment

An abbreviated description of the modem is given here; a fuller description is given elsewhere.[2] The 4-phase modulator differentially encodes a 10.7 MHz carrier so that, at each clock interval the *change* of carrier phase (0, 90, 180 or 270 degrees) carries 2 bits of the 704 kbit/s baseband stream. The clock rate is therefore 352 kHz and the transmit filter is rectangular with a flat bandwidth of about 600 kHz.

At the demodulator, the 10.7 MHz signal is passed through a raised-cosine filter (352 kHz wide at −6dB points). The carrier is recovered by the correlation (or baseband remodulation) method.[3] Two quadrature demodulators are driven by a phase-locked oscillator. The control signal for the phase-locked oscillator is generated by taking the difference of the cross-products formed from the demodulated output from each channel and the limited (sliced) output from the opposite channel. There is naturally a 4-fold ambiguity in the recovered carrier phase but this is of no consequence because of the differential coding system adopted. The clock recovery circuits operate in a conventional manner, generating half-period pulses from transitions and dividing the pulse frequency by two. Finally the bit stream is sent to the decoder with the regenerated clock pulses.

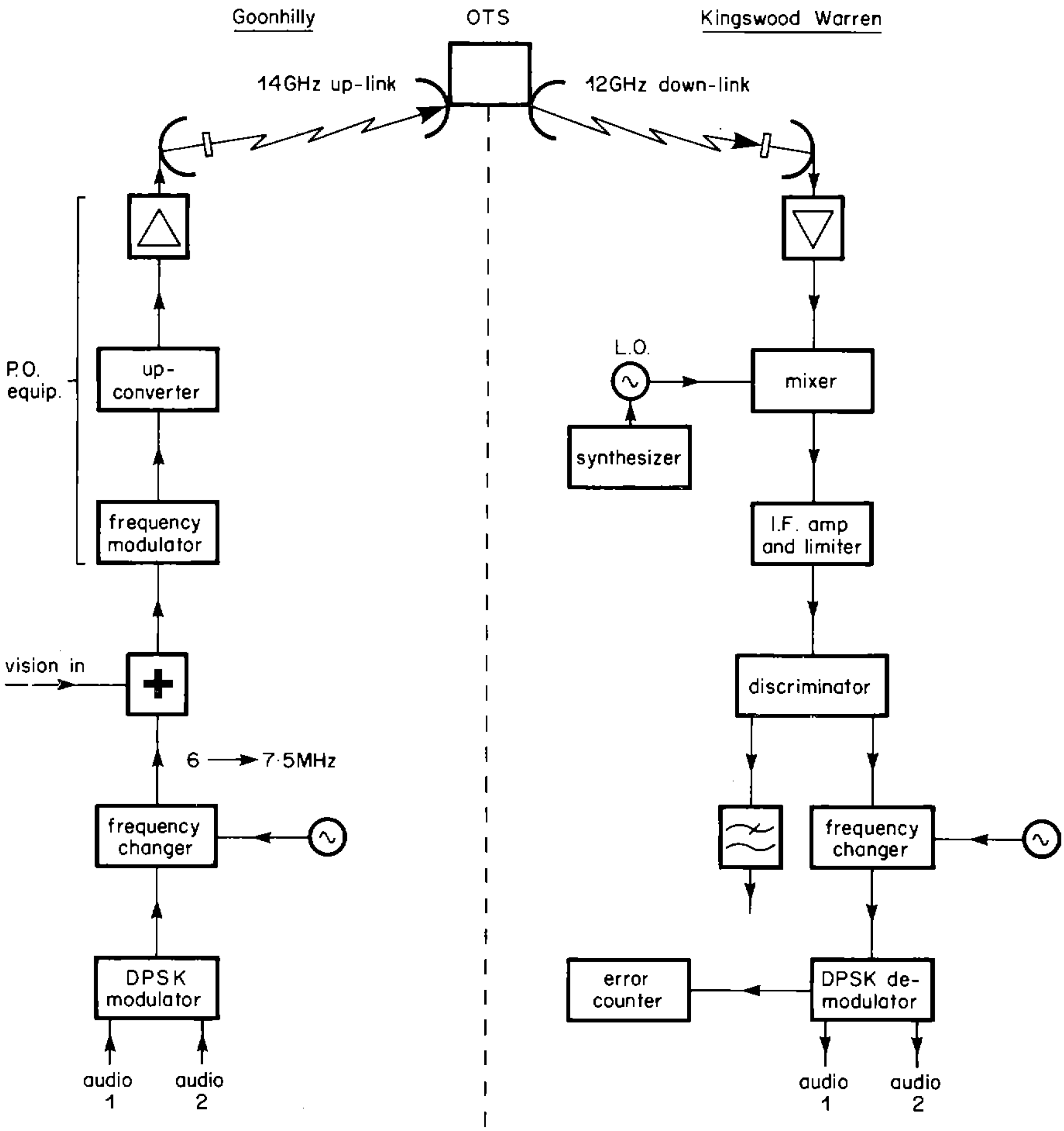

Fig. 1 - Arrangement for tests via OTS: schematic

4. The complete r.f. system used in the test

A block diagram of the whole system is shown in Fig. 1. The tests were done using signals transmitted with the spotbeam and repeater 4 on the satellite. The down-link carrier frequency was 11.64 GHz and the polarization was linear. The 2-channel sound codec and modem have already been described. The sources of picture and sound, and the parameters varied during the test, are given below.

4.1. Sources of picture and sound

Three EBU slides were chosen for the test –

Girl with Toys
Toys against Dark Background
Clown

These were accompanied by stereophonic music.

In addition, a special performance of Handel at St. John's Church, Smith Square with stereophonic sound was transmitted.

All the picture and sound material was recorded on tape and relayed from Goonhilly using an Ampex VPR-2 machine. A separate colour bar generator was used for level checking.

4.2. Energy dispersal

An energy dispersal waveform was added before the frequency modulator, applying a half-field-rate sawtooth waveform at an amplitude giving 1 MHz peak-peak deviation. This is an operational requirement at Goonhilly in the 14 – 14.5 GHz up-link band so as to minimize the level of interference to shared services.

4.3. Factors varied during the test programme

Normally the satellite transponder is operated at saturation so that the output power is stabilized at about 20w. In order to simulate atmospheric absorption, the up-link power was reduced by amounts calculated to give reductions in satellite power of 2 dB and 4 dB below saturation.

The injected d.p.s.k. subcarrier was altered in level and frequency during the tests in order to explore a range of values near the optimum. The frequency was varied in 0.5 MHz steps from 6 MHz to 7.5 MHz and the deviation of the main carrier by the subcarrier was varied ±3 dB from 1.4 MHz rms (4 MHz peak-peak).

A video peak-peak deviation of 13 MHz/V was used throughout: this is approximately the value recommended by the EBU for broadcast satellites using 27 MHz wide channels.

For the satellite tests, an additional frequency converter was added to both the modulator and the demodulator so that the subcarrier frequency could be switched to one of four values (6.0, 6.5, 7.0 and 7.5 MHz) before being added to the video signal.

5. Theoretical error rate in the 4-phase d.p.s.k. channel

The ideal theoretical error rate as a function of C/N ratio in a 4-phase p.s.k. channel, based on a model of random noise, is shown in Fig. 2. It is ideal in that it assumes perfect coherent detection, a condition that is rarely achieved in practice.

The curve is computed from the expression –

$$\text{Error probability} = 1 - \tfrac{1}{4}\left[1 + \text{erf.}\left(\sqrt{\frac{\rho}{2}}\right)\right]^2$$

where ρ is the C/N ratio in the p.s.k. channel.

It takes account of the non-gaussian nature of the phase noise. This gives a guide to errors in a d.p.s.k. system but precautions due to component error extension have to be taken.[1]

It can be seen from the curve that a 'threshold' occurs at about 10 dB C/N. In practical systems of the type that is described in this report, two principal facts militate against the ideal performance being achieved.

(i) The d.p.s.k. channel may be polluted by low-level intermodulation products in addition to random noise.

(ii) The carrier recovery circuits in the receiver may not provide perfectly coherent detection due to phase noise.

The effects of (i) and (ii) can be minimized by careful design.

Power budgets for the Goonhilly to OTS up-link and the OTS down-link to the satellite receiver terminal at Kingswood Warren are shown in Tables 1 and 2. With the available power flux density (p.f.d.) in the OTS spotbeam and a receiver G/T ratio of 20 dB/K, the carrier-to-noise ratio

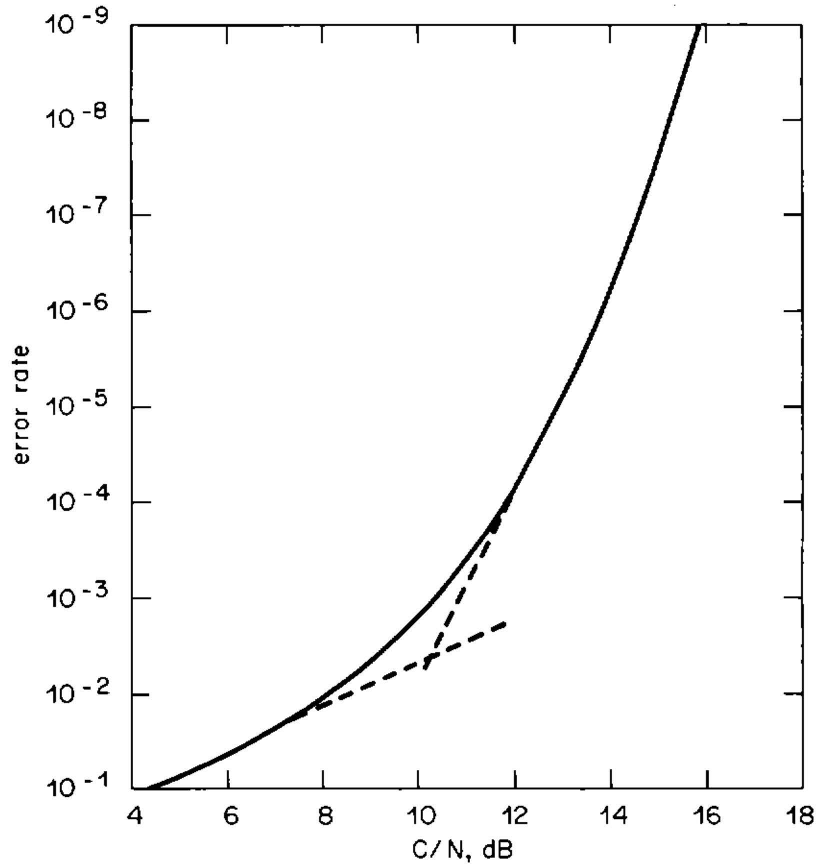

Fig. 2 - Theoretical error rate as a function of C/N ratio in the d.p.s.k. channel

TABLE 1

Up-link budget: Goonhilly to OTS.

Goonhilly power output	16 dBW
Antenna gain (19 m dish)	67 dB
Up-link e.i.r.p.	83 dBW
Path loss (clear air) at 14 GHz	207.5 dB
OTS Eurobeam 'A', gain (from Goonhilly)	25.5 dB
Received carrier power at OTS	−99 dBW
Noise figure	5 dB
Noise temperature (Earth at 290°K) 1000°K	30 dBK
Noise bandwidth (27 MHz)	74.5 dB Hz
Boltzmann's constant	−228.6 dBW Hz^{-1} K^{-1}
Noise power	−124 dBW
Up-link C/N	25 dB

TABLE 2

Down-link budget: OTS to Kingswood Warren	
OTS power output (20W less loss)	12 dBW
Spotbeam antenna gain (35.5 dB −2 dB at KW)	33.5 dB
Down-link e.i.r.p.	45.5 dBW
Path loss (clear air)	206 dB
KW antenna gain (2.4 m dish and loss)	47.5 dB
Received carrier power at KW	−113 dBW
Noise figure of pre-amplifier	4.0 dB
Noise temperature (inc. loss) 440°K	26.5 dBK
Figure of merit, G/T	20 dB K^{-1}
Noise bandwidth (27 MHz)	74.5 dB Hz
Boltzmann's constant	−228.6 dBW $Hz^{-1} K^{-1}$
Noise power	−127.5 dBW
C/N of down-link alone	14.5 dB
Degradation for 25 dB up-link C/N	0.5 dB
Effective link C/N	14.0 dB

(C/N) is calculated to be about 14 dB. This gives a weighted video signal to noise ratio of 45 dB and a five-point quality grade of 3.5.

The carrier-to-noise ratio in the d.p.s.k. channel depends not only on the carrier-to-noise ratio of the r.f. signal but also on the deviation of the main carrier by the subcarrier, and the subcarrier frequency.

It may be estimated from the expression:

$$\frac{\text{C/N in d.p.s.k. channel}}{\text{C/N in main r.f. channel}} = \left(\frac{\text{R.M.S. deviation of main carrier by subcarrier}}{\text{Frequency of subcarrier}}\right)^2 \times \left(\frac{\text{Noise bandwidth of main r.f. channel}}{\text{Noise bandwidth of d.p.s.k. channel}}\right)$$

For an example of the system used:

Subcarrier = 6.5 MHz.
Deviation of the main carrier = 1.4 MHz r.m.s.
Noise bandwidth of main r.f. channel = 27 MHz
Noise bandwidth of d.p.s.k. channel = 265 kHz.

The theoretical C/N in the subcarrier channel is therefore about 21 dB for these conditions. Laboratory tests on the d.p.s.k. system alone[2] (i.e. not added to a television signal) have shown an error performance within 1 dB of the ideal.

6. The measured performance of the OTS link

During the tests, the transmission was re-recorded at Kingswood Warren, the picture was subjectively and objectively rated and the error rate in the baseband decoder was recorded: the results are shown in Table 3.

TABLE 3

Error Rate in Sound Channels with Transponder at Saturation (C/N = 14 dB)

Subcarrier frequency	Subcarrier deviation (r.m.s.) 1.0 MHz	1.4 MHz	2.0 MHz
6.0 MHz	$>1.10^{-3}$	3.10^{-5}	1.10^{-6}
6.5 MHz	$>1.10^{-3}$	5.10^{-5}	$<1.10^{-6}$
7.0 MHz	$>1.10^{-3}$	5.10^{-5}	$<1.10^{-6}$
7.5 MHz	$>1.10^{-3}$	4.10^{-4}	3.10^{-5}

Tests were conducted with a transponder back-off of 2 and 4 dB but both vision and sound signals tended to be poor at these lower levels.

The picture grading, the C/N and the video S/N were in general agreement with the values predicted in the power budgets of Section 5. The corresponding results for the sound channel error rate fell short of ideal theory.

It was clear from an examination of the d.p.s.k. eye pattern that the onset of errors due to random noise was occurring at a higher C/N ratio because of third order cross-modulation from video components into the subcarrier channel. Second harmonic distortion was also present, which caused a form of interference analogous to 'sound-buzz'. This was found to close the eye to a lesser degree than the cross-modulation.

The non-linear effects causing cross-modulation and harmonic distortion were probably due to the combined effect of the characteristics of the modulator, the video discriminator, and to some group delay distortion in the main channel filter. Reasonably, with careful design, it should be possible to come within 2 or 3 dB of the theoretical prediction. Disturbance of the picture signal by the sound signal was only observed for the subcarrier frequency of 6.0 MHz. At this frequency the disturbance was definitely perceptible; it was imperceptible at subcarrier frequencies of 6.5 MHz and above.

7. Conclusions

The tests showed the feasibility of providing two sound channels with a Satellite broadcast transmission using a digitally modulated subcarrier.

They underlined the fact that close attention must be paid to the 'linearity' of the whole system if a good margin is to be built in against errors in the digital signal.

A subcarrier frequency of 6.5 MHz is suggested as appropriate for a two-channel system working at a rate of 704 kbit/s or thereabouts. A suitable level of subcarrier deviates the main carrier by about 1.4 MHz (r.m.s.). With these parameters no perceptible disturbance is caused to the received picture signal and, providing the effects of 'non-linearity' in the system are minimal, excellent sound quality may be achieved at a main channel carrier-to-noise ratio of 14 dB and below.

Although the tests were with two sound channels only, the digital sub-carrier system could be extended to carry more sound channels with increased bit rate. Investigations by some other Broadcasters suggest that up to six high quality channels could be carried in this way and this could be of interest to the BBC for satellite broadcasting.

8. Acknowledgement

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9. References

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